Styles of High-Sulphidation Gold, Silver and Copper Mineralisation in Porphyry and Epithermal Environments

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ABSTRACT

High-sulphidation (HS) gold, silver and/or copper deposits are generated in both the epithermal and the upper parts of the underlying porphyry environments over vertical intervals of up to 2 km. The HS deposits are generated in advanced argillic lithocaps, which are products of the absorption of acidic magmatic volatiles by voluminous groundwater systems. Mineralisation styles in HS systems reflect depth of formation as well as the interplay between structural, lithological and hydrothermal parameters. The deep parts of HS systems, at depths of >1000 m, are typified by disseminated copper±gold mineralisation comprising digenite, chalcocite and covellite in pervasive advanced argillic as well as underlying sericitic alteration. In highly telescoped systems, such mineralisation may overprint porphyry stocks and associated quartz-veinlet stockworks. Intermediate levels of HS systems commonly contain fault-controlled copper-gold mineralisation, typically as enargite in bodies of vuggy residual quartz, silicification and/or massive pyritic sulphide. The shallow parts of HS systems, at depths of <500 m, may host lithologically controlled disseminated mineralisation in which gold and/or silver tend to predominate over copper. Barren acid-leached zones formed in the steam-heated environment above paleo-water tables may be preserved above or alongside shallow HS deposits.

The exploration focus is on four principal HS mineralisation styles:

1. copper (eg Chuquicamata, Monywa) or copper-gold (Wafi) in the deep porphyry-hosted parts of systems preferably, in the case of the latter, where supergene oxidation is limited and, hence, flotation may be used for metal recovery;
2. copper±gold-bearing replacement mantos and pipes hosted by carbonate wallrocks in the deep parts of systems (eg Bisbee);
3. high-grade gold in late-stage veins or hydrothermal breccias that overprint the intermediate to shallow levels of systems (eg El Indio, Goldfield); and
4. large, bulk-mineable gold deposits in the shallow parts of systems that were subjected to supergene oxidation, thereby permitting heap-leach treatment (eg Yanacocha, Pierina).

To these preferred HS styles may be added the low-sulphidation vein or disseminated gold±silver mineralisation that is commonplace alongside many HS systems (eg Victoria at Lepanto).

INTRODUCTION

High-sulphidation (HS) gold±copper deposits have become increasingly important exploration objectives during the last decade or so, mainly in response to discovery of world-class HS epithermal deposits, such as Yanacocha and Pierina in Peru, and recognition of several porphyry copper±gold deposits, such as Wafi in Papua New Guinea and Agua Rica in Argentina, dominated by unconventional alteration and attendant HS sulphide assemblages.

These and other recent discoveries have also emphasised the diversity of HS mineralisation styles in porphyry and epithermal environments, including the transitional zone between them. Therefore, it is opportune to synthesise current information, some of which is still not widely available. The task is approached by subdividing HS mineralisation into three depth-defined zones: a deep, porphyry environment below about 1000 m; an intermediate or deep epithermal environment between about 500 and 1000 m; and a shallow epithermal environment above about 500 m depth (Figure 1; Table 1). Depth assignment is based on geological features and reconstructions, drilling information and, in a few cases, fluid-inclusion geobarometry. The styles and characteristics of HS mineralisation in each of these three environments are summarised (Figures 2 and 3) with reference to typical deposits and prospects in the Cenozoic arcs of the circum-Pacific region and Europe (Table 1). This review is concluded by considering the zoning and supergene modification of HS systems, and summarising the styles of HS mineralisation with the greatest perceived economic potential.

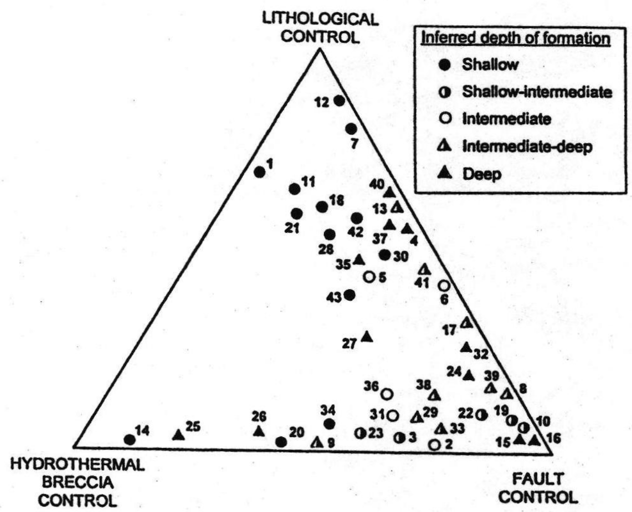

FIG 1 - Triangular graph showing the estimated roles of faults, lithologies and hydrothermal breccias in the control of 43 representative HS deposits and prospects. Their formational paleo-depths are also inferred, with deep being >1000 m, intermediate 500 - 1000 m and shallow <500 m. Note the important lithological control of shallow deposits and fault control of intermediate-depth deposits. The numbers are keyed to deposit names in Table 1.

SOME GENERAL FEATURES OF HS SYSTEMS

HS deposits are one of two principal types of epithermal deposits (eg White and Hedenquist, 1995). Their defining features include pyrite-rich, high sulphidation-state sulphide assemblages typified by enargite, luzonite, digenite, chalcocite and covellite; and advanced argillic alteration assemblages typified by quartz, alunite, pyrophyllite and kaolinite/dickite (eg Arribas, 1995). Vuggy residual quartz, the product of extreme base leaching (Stoffregen, 1987), and massive to semi-massive sulphide bodies of replacement origin, dominated by exceedingly fine-grained pyrite, melnikovite and marcasite (Sillitoe, 1983), are commonplace and mark principal fluid upflow channels. The vuggy residual quartz forms erosionally resistant ledges that are typically bordered outwards by quartz-alunite, quartz-pyrophyllite/dickite/kaolinite and argillic assemblages that reflect the progressive neutralisation and cooling of acidic fluid outwards from the upflow channels.

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TABLE 1

Selected characteristics of high-sulphidation deposits and prospects.

Deposit, country (number in Fig 1)	Size (million tonnes) and grade	Volcanic setting	Age (Ma)	Host rocks	Mineralisation style (o: oxidised, e: enriched)	Paleo-depth	Associated porphyry-type mineralisation	Associated LS mineralisation	Selected reference
Paradise Peak, USA (1)	20.6 Mt @ 2.31 g/t Au, 61.5 g/t Ag + Hg	Central-vent volcano	19 - 22	Welded ignimbrite	VQ-MQ-MS bodies with hyd bx (o)	Shallow	Porphyry Au in district	-	Sillitoe and Lorson, 1996
Goldfield, USA (2)	160 t Au, 45 t Ag, 3500 t Cu	Dome complex	21	Intermediate volcanics	Fault-cont VQ-MQ body	Intermediate		Au-Ag veins (?)	Ashley, 1974
Summitville, USA (3)	0.27 Mt @ 30 g/t Au + 9.25 Mt @ 1.6 g/t Au	Dome	22	Quartz latite porphyry	Fault-cont VQ-MQ-MS bodies and hyd bx (o)	Shallow-intermediate	Sericitic alteration at depth		Gray and Coolbaugh, 1994
Bisbee, USA (4)	55 Mt @ 5.5 % Cu, 1.4 g/t Au, 62 g/t Ag		180	Limestone	MQ-MS pipes and pods (o)	Deep	Porphyry Cu alongside	Marginal Zn-Pb replacements	Bryant and Metz, 1966
Mulatos, Mexico (5)	~135 Mt @ 1 g/t Au	Dome complex	25 - 29	Ignimbrite and volcani-clastics	Fault-cont VQ-MQ bodies and stratabound dissem (o)	Intermediate			Placer Dome Mexico, 1999
Golden Hill, Cuba (6)	1.77 Mt @ 1.2 g/t Au + 6.32 Mt @ 0.6 g/t Au, 0.33 % Cu		97	Trachyand-esitic volcanics	MS bodies (o)	Intermediate			Watkins *et al*, 1997
Pueblo Viejo, Dominican Republic (7)	>50 Mt @ 4g/t Au, 20 g/t Ag + ~100 Mt @ 3g/t Au, 23 g/t Ag	Dome complex	~130	Mudstone-sandstone and basaltic volcanics	Stratabound MQ bodies and vlets (o)	Shallow			Kesler *et al*, 1981
Santa Rosa, Peru (8)	~10 Mt @ 1.2 g/t Au		14.5[1]	Quartzite	Fault-cont vlets and dissem (o)	Intermediate -deep			Montoya *et al*, 1995
Vírgen, Peru (9)	0.27 Mt @ 1.7 g/t Au		Mid-Miocene	Quartzite	Fault-cont hyd bx (o)	Intermediate -deep			Gitennes Exploration Staff, 1998
Sipán, Peru (10)	20 Mt @ 2 g/t Au	Central-vent volcano	13.3[1]	Andesitic volcanics	Fault-controlled VQ-MQ bodies (o)	Shallow-intermediate			Candiotti and Guerrero, 1997
Yanacocha, Peru (11)	843 Mt @ 1.03 g/t Au	Dome complex	10.9 - 11.5	Dacite porphyry domes and ignimbrite	MQ-VQ bodies and hyd bx in and around domes (o)	Shallow			Turner, 1998
Pierina, Peru (12)	110 Mt @ 2.8 g/t Au, 22 g/t Ag	Dome	14.5[1]	Ignimbrite and tuff	Lith-cont VQ body (o)	Shallow		Santo Toribio Zn-Pb-Ag-Au vein	Volkert, McEwan and Garay, 1998
Colquijirca, Peru (13)	49 Mt @ 1.89 % Cu, 0.33 g/t Au (HS MS only)	Dome-diatreme complex	11[1]	Dacitic tuff, calcareous sedimentary rocks	Dissem in tuff, MS bodies in calcareous units	Intermediate -deep		Carbonate-replacement Zn-Pb-Ag mantos	Vidal, Proaño and Noble, 1997
Choque-limpie, Chile (14)	11 Mt @ 2.23 g/t Au, 87 g/t Ag	Summit domes in central-vent volcano	7	Andesite porphyry	Hyd bx (o)	Shallow		LS Au-Ag vein	Gröpper *et al*, 1991
Chuquica-mata, Chile (15)	10 520 Mt @ 0.94 % Cu		31 - 34	Monzogranite porphyry	Fault-cont MS veins, vlets and dissem (o, e)	Deep	Overprinted on porphyry Cu-Mo		Fréraut, Ossandón and Gustafson, 1997
MM, Chile (16)	325 Mt @ 0.96 % Cu		33 - 34	Granodiorite	Fault-cont MS veins and vlets	Deep	Porphyry Cu-Mo juxtaposed structurally		Sillitoe *et al*, 1996

TABLE 1 (continued)

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Deposit, country (number in Fig 1)	Size (million tonnes) and grade	Volcanic setting	Age (Ma)	Host rocks	Mineralisation style (o: oxidised, e: enriched)	Paleo-depth	Associated porphyry-type mineralisation	Associated LS mineralisation	Selected reference
El Guanaco, Chile (17)	~30 t Au + 11.5 Mt @ 1.77 g/t Au	Caldera(?)	~49	Ignimbrite and andesitic volcanics	Fault-cont MQ-VQ and related strata-bound dissem (o, e)	Intermediate-deep			Llaumett, 1979
La Coipa, Chile (18)	~70 Mt @ 1.37 g/t Au, 82 g/t Ag	Dome complex	20-24	Dacitic volcanics and volcani-clastics + lutite-arenite	VQ-MS bodies and hyd bx (o)	Shallow			Oviedo *et al*, 1991
El Indio, Chile (19)	23.2 Mt @ 6.6 g/t Au, 50 g/t Ag, ~4 % Cu + 0.2 Mt @ 209 g/t Au (DSO)	Dome (?)	11 - 12.5[2]	Ignimbrite	Fault-cont MS-MQ veins	Shallow-intermediate		Río del Medio Au-Ag veins	Jannas *et al*, 1990
Tambo, Chile (20)	37.2 Mt @ 4.18 g/t Au + 42 Mt @ 1 g/t Au	Dome (?)	7.5[2]	Ignimbrite	Fault-cont hyd bx (o)	Shallow			Siddeley and Araneda, 1990
Pascua, Chile (21)	340 Mt @ ~1 g/t Au, 30 g/t Ag		7.4 - 8.0[2]	Ignimbrite	Lith-cont VQ-MQ and hyd bx (o)	Shallow	Barren porphyry stockwork below		
Cerro Rico, Bolivia (22)	86 000 t Ag	Dome	13.8	Rhyodacite porphyry and lake beds	MQ-VQ body with veins (o)	Shallow-intermediate	Sn-base metal veins beneath		Sillitoe *et al*, 1998
Cachi Laguna, Bolivia (23)	1.7 Mt @ 1.5 g/t Au, 112 g/t Ag	Summit dome in central-vent volcano	Pliocene	Andesite porphyry	VQ, MS and hyd bx bodies (o)	Shallow			
Nevados de Famatina, Argentina (24)	1 Mt @ 11 g/t Au, 80 g/t Ag, 3 % Cu + 90 Mt @ 0.9 g/t Au		3.8	Phyllite	Dissem, vlets and veins	Deep	5 porphyry Cu-Mo-Au prospects alongside	Ag-Au veins	Losada-Calderón and McPhail, 1996
Agua Rica, Argentina (25)	750 Mt @ 0.62 % Cu, 0.037 % Mo, 0.24 g/t Au		4.9 - 6.3	Porphyry and metamorphic rocks	Hyd bx and stockwork (e)	Deep	Overprinted on porphyry Cu-Mo-Au mineralisation		Perelló *et al*, 1998
Monywa, Myanmar (26)	1000 @ 0.41 % Cu	Dome complex	19	Andesite porphyry	Hyd bx dykes, vlets and dissem (e)	Deep	Porphyry Cu-Mo beneath	Au-Ag veins	Win and Kirwin, 1998
Motomboto, Indonesia (27)	~3 Mt @ 1.5 g/t Au, 60 g/t Ag, 2 % Cu	Dome	1.9	Dacite porphyry and volcanics	Fault- and dome-cont VQ-MQ-MS bodies with hyd bx	Deep	Sungai Mak porphyry Cu-Au alongside	Au veins	Perelló, 1994
Lerokis and Kali Kuning, Indonesia (28)	5.1 Mt @ 4.36 g/t Au, 128 g/t Ag, 50 % barite	Domes (?)	4.7	Andesitic volcanics	MS bodies and massive barite (o)	Shallow			Sewell and Wheatley, 1994
Zijinshan, China (29)	~100 Mt @ 1 % Cu + 2 Mt @ 5g/t Au	Dome	100 - 105	Granite and dacite porphyry dome	VQ-MQ bodies, hyd bx, MS veins and vlets	Intermediate-deep	Porphyry Cu-Mo alongside		So *et al*, 1998
Kasuga, Japan (30)	4.1 Mt @ 2.8 g/t Au, 0.8 g/t Ag	Central-vent volcanoes in caldera (?)	5.0	Andesitic volcanics	VQ-MS body (o)	Shallow		Kago Au veins	Hedenquist *et al*, 1994

TABLE 1 (continued)
Selected characteristics of high-sulphidation deposits and prospects.

Deposit, country (number in Fig 1)	Size (million tonnes) and grade	Volcanic setting	Age (Ma)	Host rocks	Mineralisation style (o: oxidised, e: enriched)	Paleo-depth	Associated porphyry-type mineralisation	Associated LS mineralisation	Selected reference
Chinkuashih, Taiwan (31)	~20 Mt @ 4.6 g/t Au, 9 g/t Ag + 119 000 t Cu	Dome complex	1.0 - 1.3	Dacite porphyry and sandstone-shale	Fault-cont MS-VQ bodies and hyd bx pipes	Intermediate		Au-Ag-Zn-Pb quartz-carbonate veins	Tan, 1991
Guinaoang, Philippines (32)	~30 Mt @ 0.5 % Cu, 0.5 g/t Au (HS only)	Dome-diatreme	3.5	Andesitic volcanics	Partly fault-cont dissem	Deep	Porphyry Cu-Au beneath		Sillitoe and Angeles, 1985
Lepanto, Philippines (33)	36.3 Mt @ 2.9 % Cu, 3.4 g/t Au, 10.8 g/t Ag	Dome-diatreme	1.5 - 1.2	Andesitic and dacitic volcanics	Fault-cont MS-VQ-MQ body with hyd bx and veins	Intermediate-deep	Porphyry Cu-Au down plunge	Victoria Au-Ag-base metal veins	Hedenquist, Arribas and Reynolds, 1998
Nalesbitan, Philippines (34)	8 Mt @ 3.5 g/t Au	Central-vent volcano (?)	Pliocene	Andesitic volcanics	Fault-cont MQ and hyd bx (o)	Shallow			Sillitoe *et al*, 1990
Tampakan, Philippines (35)	1400 Mt @ 0.55 % Cu, 0.24 g/t Au	Central-vent volcano	Pliocene (?)	Andesitic volcanics	Dissem, vlets and hyd bx	Deep	Porphyry Cu-Au below		Madera and Rohrlach, 1998
Nena, PNG (36)	51 Mt @ 2.2 % Cu, 0.6 g/t Au + 18 Mt @ 1.4 g/t Au	Central-vent volcano	13	Andesitic volcanics	Fault-cont MS-VQ-MQ body with hyd bx	Intermediate	Several porphyry Cu-Au alongside		Bainbridge, Corbett and Leach, 1994
Wafi, PNG (37)	100 Mt @ 1.3 % Cu, 0.6 g/t Au		14	Meta-sedimentary rocks	Dissem	Deep	Porphyry Cu-Au below	Dissem Au alongside	Tau-Loi and Andrew, 1998
Bor, Yugoslavia (38)	110 Mt @ ~1 % Cu, 0.4 g/t Au	Central-vent volcano (?)	Late Cretaceous	Andesitic volcanics	Fault (?)-cont MS and dissem bodies	Intermediate-deep	Porphyry Cu-Mo below		Jankovic, 1990
Chelopech, Bulgaria (39)	52.1 Mt @ 1.4 % Cu, 3.3 g/t Au	Central-vent volcano or dome complex	Late Cretaceous	Andesitic volcanics	MS bodies	Intermediate-deep	Porphyry Cu-Mo alongside		Tersiev, 1968
Petelovo, Bulgaria (40)	16 Mt @ 0.69 g/t Au	Central-vent volcano	Late Cretaceous	Andesitic volcanics	Dissem	Deep	Porphyry Cu-Mo below		
Recsk, (Lahóca) Hungary (41)	3 Mt @ 0.8 % Cu + 36.7 Mt @ 1.4 g/t Au	Central-vent volcano	Late Eocene	Andesitic volcanics	MS body and dissem	Intermediate-deep	Porphyry Cu-Mo below		Baksa, 1975
Furtei, Italy (42)	2.8 Mt @ 3.1 g/t Au + Ag, Cu	Dome-diatreme	23 - 25	Diatreme breccia and ignimbrite	Fault- and dome-cont VQ-MS bodies with hyd bx (o)	Shallow		Au-Ag-quartz-barite veins	Ruggieri *et al*, 1997
Rodalquilar, Spain (43)	10 t Au	Caldera margin, ring domes	10.4	Ignimbrite and rhyolite domes	Quartz veins and vlets, hyd bx and VQ bodies (o)	Shallow	Sericitic alteration at depth	Pb-Zn-Ag-Au quartz veins	Arribas *et al*, 1995

Supplementary age data: 1 Noble and McKee (1997), 2 Clavero *et al* (1997). Abbreviations: bx, breccia; cont, controlled; dissem, disseminated; hyd, hydrothermal; lith, lithologically; MQ, massive quartz (silicification); MS, massive sulphide; vlets, veinlets; VQ, vuggy quartz

HS deposits constitute all or parts of lithocaps, which are extensive zones of advanced argillic and argillic alteration generated between the subvolcanic intrusive environment and the paleosurface (Sillitoe, 1995). HS mineralisation in the porphyry environment is formed in the roots of lithocaps, whereas mineralisation designated as deep or shallow epithermal was emplaced at depths shallower than the intrusions, through to the paleosurface. Many lithocap remnants, however, contain numerous siliceous ledges that are apparently devoid of appreciable HS mineralisation. By the same token, there is no requirement for the underlying subvolcanic intrusions to possess economically significant porphyry or other types of mineralisation.

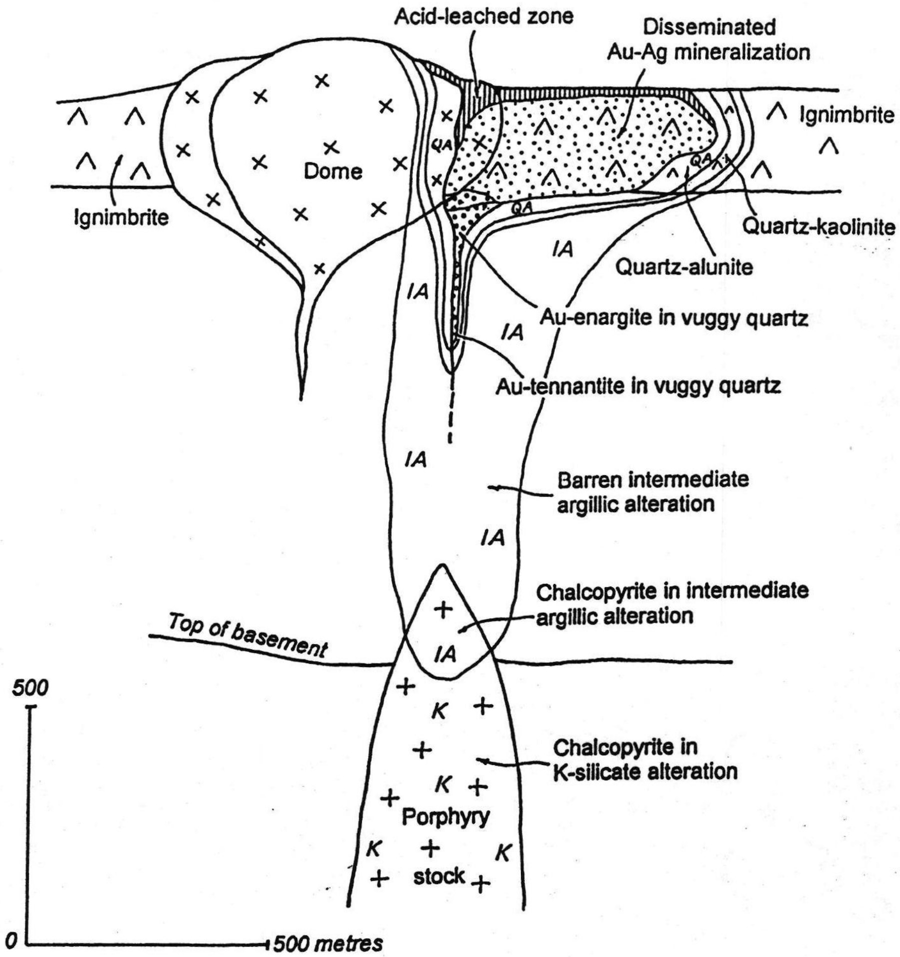

FIG 2 - Schematic reconstruction of a dome-related HS system separated spatially from the underlying porphyry copper environment. Note the upward changes from copper to gold/silver and fault-controlled to disseminated mineralisation. The paleosurface is marked by acid-leached rock of steam-heated origin.

Most lithocaps are present in arc terranes characterised by porphyry copper-molybdenum/gold deposits, but similar zones of advanced argillic and argillic alteration are also recognised in shallowly eroded lithophile-metal provinces, such as the Bolivian tin-silver belt (Sillitoe *et al*, 1998). The more reduced, ilmenite-series character of the magmatism seems to explain why the HS mineralisation in such lithocaps is dominated by silver-antimony-tin instead of the more normal gold-(silver)-arsenic-copper association (Sillitoe *et al*, 1998).

Based on fluid-inclusion and isotopic studies of several of the HS systems considered herein, there is broad agreement that advanced argillic alteration is the product of oxidised and acidic fluids generated by condensation of magmatic volatiles enriched in SO_2, HCl and HF into meteoric water (eg Arribas *et al*, 1995; Hedenquist *et al*, 1994; Hedenquist, Arribas and Reynolds, 1998; Ruggieri *et al*, 1997; So *et al*, 1998). The fluid responsible for the subsequent gold, silver and copper deposition in HS systems is generally thought to be relatively cool and dilute and to possess an appreciable meteoric water component, although its ultimate origin remains uncertain. Progressive admixture of meteoric water and ascendant magmatic volatiles (Sillitoe, 1983; Heinrich *et al*, in press), magmatic brine (White, 1991; Hedenquist *et al*, 1994) or less-saline magmatic fluid (Hedenquist, Arribas and Reynolds, 1998) have all been proposed. Recent evidence for preferential volatile transport of copper, gold and arsenic under high-pressure conditions (eg Heinrich *et al*, in press) certainly makes the first of these alternatives an attractive proposition.

DEEP HS MINERALISATION

HS gold, silver and copper mineralisation may be separated from the underlying porphyry environment by several hundred vertical metres, as documented by deep drilling at Summitville, Colorado (Gray and Coolbaugh, 1994), or may be juxtaposed with it or superimposed on it (Figures 2, 3 and 4). Juxtaposition and superposition of porphyry and HS mineralisation result from telescoping, generally in response to profound surface degradation by uplift-induced erosion or, perhaps less commonly, volcanic collapse during the hydrothermal lifespans of systems (Sillitoe, 1994). Telescoping of HS over porphyry mineralisation is controlled by zones of maximum permeability, which was provided by syn-mineral faults at Chuquicamata (Lindsay *et al*, 1995) and MM (Sillitoe *et al*, 1996), a swarm of fault-controlled breccia dykes at Monywa (Win and Kirwin, 1998) and a hydrothermal breccia pipe at Agua Rica (Perelló *et al*, 1998). Where HS mineralisation is telescoped over that of porphyry type, quartz-veinlet stockworks generated in conjunction with K-silicate alteration may occur as remnants in the overprinted advanced argillic assemblages, as observed at Agua Rica, Wafi and Tampakan (Figures 4 and 5). Locally, patches of K-silicate alteration may even survive the overprint (eg Agua Rica: Perelló *et al*, 1998).

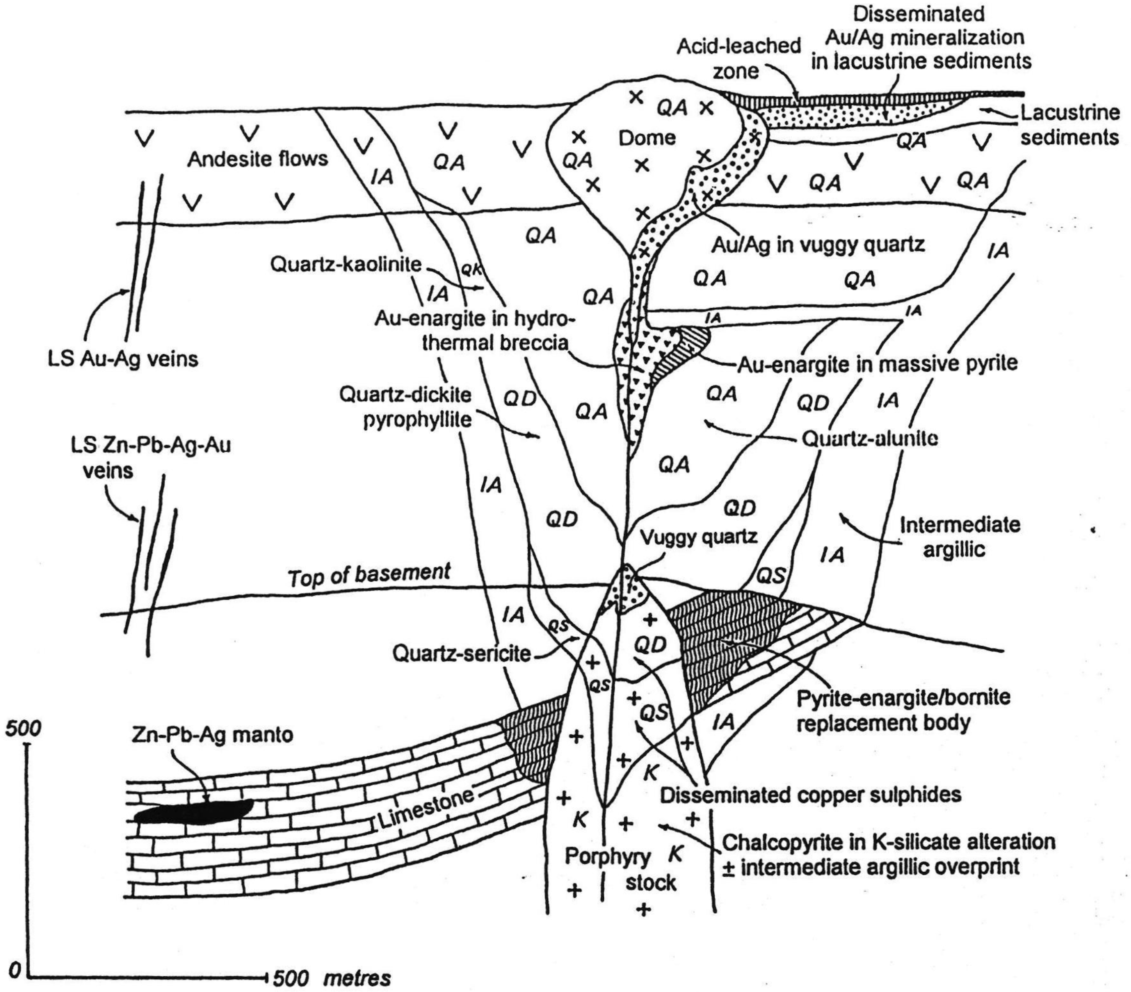

FIG 3 - Schematic reconstruction of a dome-related HS system telescoped over the upper parts of the underlying porphyry copper environment. Note the upward changes from copper sulphides to enargite, copper to gold/silver, sericitic to advanced argillic alteration and disseminated to fault-controlled and back to disseminated mineralisation. The paleosurface is characterised by acid-leached rock of steam-heated origin, and the margin of the system by LS zinc, lead and precious-metal mineralisation.

The zones of transition between HS and porphyry mineralisation are typically characterised by downward changes from advanced argillic alteration, commonly dominated by quartz-dickite±pyrophyllite and subsidiary diaspore, to sericitic (quartz-sericite-pyrite) alteration (Figure 3), as observed at Potosí (Sillitoe *et al*, 1998), Wafi (Tau-Loi and Andrew, 1998; Figure 5), Zijinshan (So *et al*, 1998), Petelovo (R H Sillitoe, unpublished data) and Rodalquilar (Arribas *et al*, 1995). Sericitic alteration grades downwards into K-silicate alteration containing chalcopyrite-(bornite)-pyrite (Figure 3), in some deposits, especially in the western Pacific region, through a transitional intermediate argillic (illite/sericite-chlorite-pyrite) zone (Guinaoang: Sillitoe and Angeles, 1985; Tampakan: Madera and Rohrlach, 1998; Wafi: Tau-Loi and Andrew, 1998; Figure 5). HS mineralisation is commonly confined to the advanced argillic alteration, but at some localities it extends downwards into the sericitic zone, most spectacularly over a structurally controlled vertical interval of at least 1000 m at Chuquicamata (Fréraut, Ossandón and Gustafson, 1997), but also at Guinaoang (Sillitoe and Angeles, 1985), Petelovo and elsewhere. In the deepest parts of other HS mineralised zones, sericite may be accompanied by dickite (Wafi: Corbett and Leach, 1998; Figure 5) or pyrophyllite (MM: Sillitoe *et al*, 1996).

The deep to intermediate-level parts of some HS systems contain bodies of massive siliceous alteration, including both silica introduction, ie silicification, and residual vuggy quartz. Bodies of silicification and vuggy quartz, partly incorporated into hydrothermal breccia, occur within the advanced argillic zone at Wafi (Tau-Loi and Andrew, 1998), but occur between advanced argillic and overlying intermediate argillic alteration at Tampakan (Madera and Rohrlach, 1998); however, the silicification at Bor reportedly spans the interval between the base of the main HS mineralisation and the underlying porphyry environment (Jankovic, 1990; Herrington, Jankovic and Kozelj, 1998). The vuggy quartz, apparently localised by the top of the porphyry stock at Wafi (Figure 5), contains copper-bearing sulphides, whereas silicification tends generally to be barren unless hydrothermally brecciated. The intermediate argillic alteration reported above advanced argillic alteration at Tampakan may be compared with similar intermediate argillic or chloritic patches in many lithocaps (Figure 3), which are believed to reflect zones of somewhat lower permeability.

The deep parts of the HS environment are characterised by high sulphidation-state sulphides comprising several of bornite, digenite, chalcocite and covellite, all of them hypogene in origin. Enargite is ubiquitous but generally subordinate in amount, as is

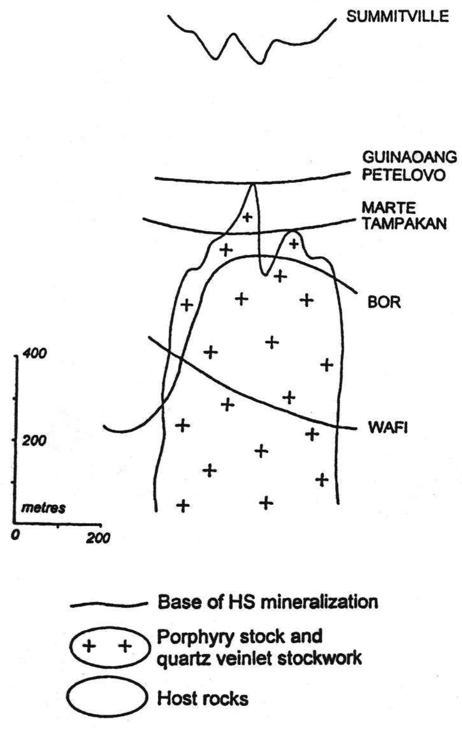

FIG 4 - Schematic relations between the bases of HS mineralisation and tops of porphyry-type mineralisation as defined by the presence of porphyry stocks and/or quartz-veinlet stockworks. Note the varied degrees of telescoping. Data from Gray and Coolbaugh (1994), Jankovic (1990), Madera and Rohrlach (1998), Sillitoe and Angeles (1985), Tau-Loi and Andrew (1998), Vila *et al* (1991) and the writer's own observations of the deposits concerned.

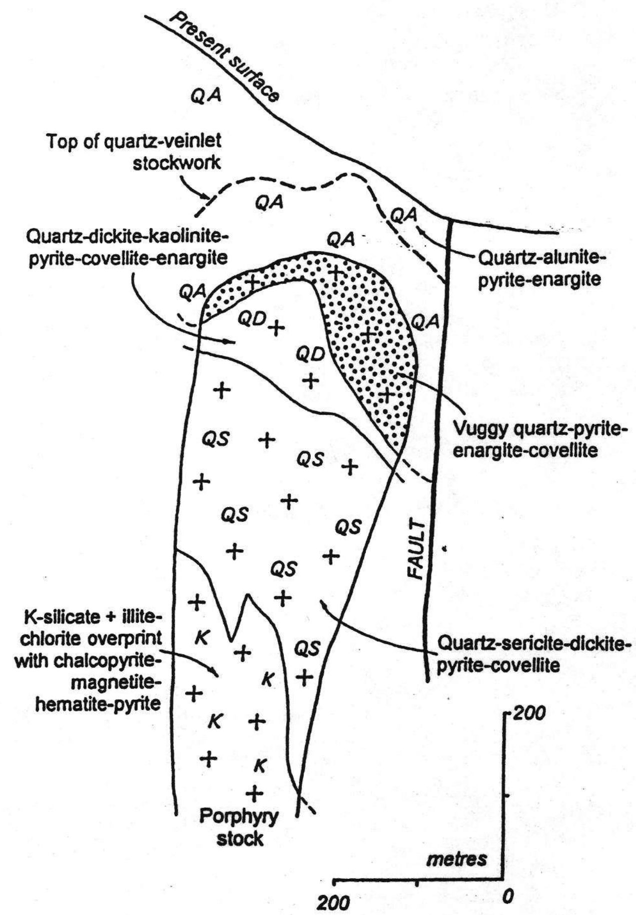

FIG 5 - Simplified alteration-mineralisation zoning in and immediately above the porphyry stock in the highly telescoped Wafi porphyry copper-gold deposit, Papua New Guinea. Note the upward changes from K-silicate/intermediate argillic through sericitic to advanced argillic alteration, with residual vuggy quartz apparently being localised by the roof of the stock, and from chalcopyrite through covellite to enargite mineralisation. The upper limit of the A-type quartz-veinlet stockwork is about 100 m above the roof of the stock. Compare figure with those presented by Corbett and Leach (1998) and Tau-Loi and Andrew (1998).

any chalcopyrite. These copper-rich sulphides are commonly present as partial replacements of dispersed pyrite, with resulting textures that mimic those typical of supergene copper sulphide enrichment (Figure 6). The pyrite that underwent this 'hypogene copper enrichment' was formed after hypogene leaching and removal of pre-existing chalcopyrite±bornite introduced, commonly in quartz-veinlet stockworks, with K-silicate alteration (Figure 6). Veinlet sulphides are uncommon under deep HS conditions, although unusual massive pyrite-enargite-sphalerite veins concluded the HS event at Chuquicamata (Fréraut, Ossandón and Gustafson, 1997). These deep copper-rich HS zones may contain appreciable (≥0.5 g/t) gold (Guinaoang, Wafi), minor gold plus molybdenum (Agua Rica, Tampakan), molybdenum alone (Chuquicamata, MM, Famatina) or neither metal in appreciable amounts (Monywa).

HS mineralisation assigned a fairly deep origin commonly affected subvolcanic basement rocks. This situation is probably more common where volcanic sequences are relatively thin, as in flow-dome complexes as opposed to stratovolcanoes. The basement rocks range from extremely unreactive quartzite at Santa Rosa (Montoya *et al*, 1995) and Vírgen (Gitennes Exploration Staff, 1998), phyllite at Nevados de Famatina (Losada-Calderón and McPhail, 1996) and equigranular felsic plutons at MM (Sillitoe *et al*, 1996) and Zijinshan (So *et al*, 1998) to receptive calcareous lithologies at Bisbee (Bryant and Metz, 1966) and Colquijirca (Vidal, Proaño and Noble, 1997). The basement rock-hosted HS mineralisation at Navados de Famatina and Bisbee is located alongside porphyry copper-molybdenum mineralisation displaying quartz-sericite and quartz-sericite-pyrophyllite alteration, respectively (Losada-Calderón and McPhail, 1996; Bryant and Metz, 1966; Figure 3). The unreactive basement rocks contain mineralisation

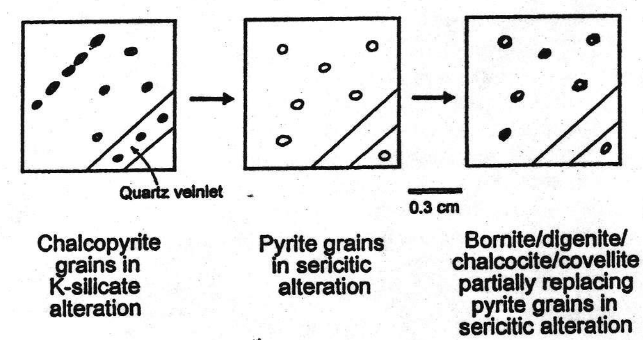

FIG 6 - Sequential hypogene sulphide mineralogy developed in the roots of some HS environments. Sericitic overprinting of K-silicate alteration causes leaching of chalcopyrite and introduction of disseminated pyrite at different sites. Subsequently, pyrite is partially replaced by high sulphidation-state sulphides causing 'hypogene enrichment'. Care is required to avoid confusion of this process with the superficially similar products of supergene enrichment during weathering.

hosted by minor faults, fractures and hydrothermal breccias, whereas receptive calcareous horizons are replaced by massive quartz-pyrite bodies cut and bordered by enargite (Vidal, Proaño and Noble, 1997) or chalcopyrite-bornite (Bryant and Metz, 1966). Einaudi (1982) pointed out that quartz-pyrite is the equivalent of skarn under the relatively low-temperature and low-pH conditions requisite for advanced argillic alteration.

Advanced argillic alteration extends deeply along the sides of porphyry stocks in some systems, instead of overprinting the stocks themselves as illustrated in Figure 3. Such marginal advanced argillic zones are mineralised at Nevados de Famatina and Bisbee, as mentioned above, but are reportedly barren at Bor (Figure 4) and elsewhere (eg Frieda River, Papua New Guinea: Corbett and Leach, 1998). Such downward-penetrating prongs of barren advanced argillic alteration, called 'barren advanced argillic shoulders' by Corbett and Leach (1998), are simply the roots of lithocaps controlled by permeability contrasts that existed between stocks and their immediate wallrocks.

INTERMEDIATE-DEPTH HS MINERALISATION

HS mineralisation hosted by bodies of vuggy residual quartz and/or semi-massive to massive pyritic sulphides may be encountered throughout the HS environment, but is most typical of intermediate depths, in the deep epithermal environment (Figures 2 and 3).

The vuggy quartz, commonly in close association with silicification, may occur as moderately dipping to steep, roughly tabular, fault- or fracture-controlled ledges, as at Goldfield (Ashley, 1974), Summitville (Gray and Coolbaugh, 1994) and Sipan (Candiotti and Guerrero, 1997). Larger vuggy quartz bodies, like the largest one at Summitville, may exist at fault and fracture intersections. More extensive, lithologically controlled bodies of vuggy residual quartz plus silicification are also known, like the huge rhyodacite porphyry dome-hosted body at Potosí which contains abundant aluminium phosphate-sulphate (APS) minerals (Sillitoe *et al*, 1998). HS sulphide mineralisation typically occupies the hydrothermally generated cavities in the vuggy quartz and any cross-cutting fractures.

The massive sulphides commonly occur as fault- and fracture-controlled veins, as described from El Guanaco (Llaumett, 1979) and El Indio (Jannas *et al*, 1990), whereas one or more ovoid to pipe-like massive sulphide bodies typify Golden Hill (Watkins *et al*, 1997), Chelopech (Terziev, 1968) and Lahóca at Recsk (Baksa, 1975). All these massive sulphide bodies, except perhaps for the veins at El Indio, are dominated by iron sulphides, which include an early massive, fine-grained, locally banded variety (Sillitoe, 1983) as well as later coarser-grained generations of pyrite.

Some of the largest deep epithermal HS deposits, such as the fault-controlled Lepanto (Garcia, 1991; Hedenquist, Arribas and Reynolds, 1998), Nena (Bainbridge, Corbett and Leach, 1994) and Bor (Jankovic, 1990) deposits, display complex combinations of vuggy quartz, silicification, pyritic massive sulphide and sulphide-cemented hydrothermal breccia. At Bor, the massive sulphides are bordered by voluminous disseminated and veinlet mineralisation whereas, at Lepanto, flanking tensional veins are widespread.

Enargite is the principal copper-bearing sulphide mineral in most of these deep epithermal HS deposits and is generally accompanied by subsidiary quantities of luzonite and/or tennnatite as well as the copper sulphides (covellite, chalcocite, digenite) that predominate at deeper levels. Gold, in the 1 - 5 g/t range, is found in most of these vuggy quartz and massive sulphide bodies and appears to be closely related to the copper-bearing sulphides. At many localities, however, as exemplified by El Indio (Jannas *et al*, 1990) and Lepanto (Hedenquist, Arribas and Reynolds, 1998), gold and several telluride minerals are paragenetically late and were precipitated during or after partial replacement of enargite by tennantite and chalcopyrite, indicative of lower sulphidation-state fluid. A downward change from enargite to tennantite±chalcopyrite is also observed in some deposits (eg Summitville: Stoffregen, 1987; El Indio: Jannas *et al*, 1990; Lepanto: Garcia, 1991). Potosí is the principal exception to these mineralogical generalisations, because it lacks arsenic (and hence enargite) and gold. Nearly complete supergene oxidation precludes proper determination of the sulphides present in the vuggy quartz body at Potosí, although pyrite and acanthite are prominent in unoxidised remnants (Sillitoe *et al*, 1998).

Most of the copper and gold in deep epithermal HS deposits is confined to the vuggy quartz and associated silicification and to the massive sulphides. However, especially in the larger deposits, lower copper and gold contents may extend beyond these highly siliceous and sulphidic rocks into the inner parts of alteration haloes, which are normally composed of quartz and alunite. Nevertheless, outer argillic alteration zones are essentially barren.

Silicification, vuggy quartz and most massive sulphide are alteration products of pre-existing rocks, with any open-space filling generally being confined to hydrothermal breccias and cavities. At several deposits, however, late-stage veins showing evidence for incremental open-space filling overprinted the vuggy quartz or massive sulphide bodies. These comprise relatively minor, but gold-rich, quartz-base metal and barite-base metal veins at Lepanto (Hedenquist, Arribas and Reynolds, 1998) and Summitville (Gray and Coolbaugh, 1994), respectively, but important bonanza-grade gold-quartz-sulphide veins at El Indio (Jannas *et al*, 1990). To these may be added late-stage hydrothermal breccias containing bonanza gold grades at Goldfield (Ransome, 1909), Chinkuashih (Tan, 1991) and, at a shallower level, Rodalquilar (Arribas *et al*, 1995). Some of these late vein and breccia events provide mineralogical evidence for a decreased sulphidation state of the fluid involved, as shown by the predominance of tennantite-chalcopyrite over enargite in the bonanza quartz veins at El Indio.

SHALLOW HS MINERALISATION

Although structural control of HS mineralisation and its association with vuggy quartz and massive sulphides are still prominent features of the shallow epithermal environment, lithological permeability and hydrothermal brecciation play much more important roles. In these shallow settings, fault- and fracture-fed fluids under relatively low hydrostatic pressure conditions are capable of permeating large volumes of porous or fractured units. Such units may be only partially lithified at the time of HS mineralisation, as suggested, for example, by the erratic nature of some of the sulphide veining in carbonaceous mudstone at Pueblo Viejo.

A surprising number of the largest HS gold deposits, all of them in the western Americas (Figure 1; Table 1), are hosted by moderately to poorly welded ignimbrite (ash-flow tuff). Such major deposits as Mulatos (Placer Dome Mexico, 1999), Pierina (Volkert, McEwan and Garay, 1998), Yanacocha (Klein, Barreda and Harvey, 1997), Pascua (Siddeley and Araneda, 1990), Tambo (Siddeley and Araneda, 1986) and Paradise Peak (Sillitoe and Lorson, 1994) are hosted partly or wholly by ignimbrite. In addition, the small shallow Rodalquilar deposit and the fault-controlled, intermediate-level deposits at El Guanaco and El Indio also occur mainly in ignimbrite. The gold mineralisation at Pierina, parts of Yanacocha, Pascua and Paradise Peak is dispersed through its host ignimbrites as well as being present in cross-cutting hydrothermal breccia bodies, whereas the Tambo deposit is confined entirely to structurally controlled hydrothermal breccia bodies. Aquitards, such as andesitic flows

at Paradise Peak and devitrified vitrophyre at the bases of overlying ignimbrite units at Yanacocha and Paradise Peak, provide sharp outer limits to mineralisation in places. Other permeable lithologies, such as bedded tuffs and volcaniclastic sedimentary rocks, in parts of Mulatos (Placer Dome Mexico, 1999) and at La Coipa (Oviedo *et al*, 1991), and lacustrine mudstone at Pueblo Viejo (Kesler *et al*, 1981), are also able to 'soak up' large volumes of mineralising fluid to generate major HS deposits. The permeability contrasts between the mineralised units and 'tight' subjacent rocks (eg spilitised basalt at Pueblo Viejo: Kesler *et al*, 1981; andesite at Pierina: Volkert, McEwan and Garay, 1998; Triassic lutite and arenite at La Coipa: Oviedo *et al*, 1991) seem to have been a major control on the development of bulk-tonnage mineralisation at several deposits.

Although some of these shallow HS deposits are closely related to well-defined bodies of vuggy residual quartz, as at Pierina (Volkert, McEwan and Garay, 1998), several of the others, including Yanacocha, Pascua, Tambo, La Coipa and Paradise Peak, display complex mixtures of vuggy quartz, massive silicification and quartz-cemented hydrothermal breccia. Massive pyritic sulphide occurs in the deeper parts of Paradise Peak (Sillitoe and Lorson, 1994) and, prior to oxidation, is thought likely to have been more abundant in several of these other large, shallow deposits. The mineralised breccias are likely to be generated by self-sealing of upflow conduits by quartz deposition and the consequent overpressuring of ascendant two-phase fluids. Such mineralised breccias are therefore inter-mineral in timing, and they commonly contain clasts of vuggy residual quartz, typically a product of early low-pH fluids in HS systems. Hydrothermal breccias with matrices composed of alunite (eg La Coipa: Oviedo *et al*, 1991) or even intergrown alunite and barite (eg El Tambo: Siddeley and Araneda, 1986) may, however, also be well mineralised. Other breccias are generated late in HS systems and are poorly mineralised or barren, an example being the rock flour-cemented breccia at Choquelimpie (Gröpper *et al*, 1991).

Small HS deposits in the shallow epithermal environment tend to be geometrically simpler and generally hosted by lithologically and/or structurally localised vuggy quartz±iron sulphide bodies. Those, such as Kasuga, in the Nansatsu district of southwestern Japan occur in tuffs above massive andesite (Hedenquist *et al*, 1994), whereas those at Furtei are localised around the intersections of faults and andesite porphyry dome contacts within diatreme breccia (R H Sillitoe, unpublished data; Ruggieri *et al*, 1997). The Choquelimpie (Gröpper *et al*, 1991), Nalesbitan (Sillitoe *et al*, 1990) and Cachi Laguna (R H Sillitoe, unpublished data) deposits are hosted principally by hydrothermal breccia.

Several shallow epithermal HS gold deposits and their accompanying advanced argillic alteration have been shown by drilling to terminate abruptly downwards, generally as minor quartz-pyrite veinlets with only low gold contents (Figure 2). Good examples are provided by Pierina (Volkert, McEwan and Garay, 1998), Nalesbitan (Sillitoe *et al*, 1990), Kasuga (Hedenquist *et al*, 1994) and Rodalquilar (Arribas *et al*, 1995). The evidence suggests that the bases of these deposits may represent the sites at which acidic fluid was initially generated as the result of meteoric water absorption of ascendant magmatic volatiles. If the ore-forming fluid was formed in a similar manner, high-grade feeder zones are not to be expected beneath these deposits.

The total sulphide content of shallow HS bodies tends generally to be less than that typical of deposits assigned to intermediate levels, although the same suite of high sulphidation-state sulphides is present. With the exception of the iron sulphides, enargite and covellite seem to be the most common sulphide species, although luzonite, stibnite-bismuthinite (eg Paradise Peak: Sillitoe and Lorson, 1994) and sphalerite (eg Choquelimpie: Gröpper *et al*, 1991; Pueblo Viejo: Kesler *et al*, 1981; Furtei: Ruggieri *et al*, 1997) are widely reported. Notwithstanding the effects of sulphide oxidation, it appears that shallow HS deposits contain less copper than the deeper deposits and, hence, constitute mainly gold±silver orebodies. The elevated Ag/Au ratios of some shallow HS deposits, such as Paradise Peak (Ag/Au=32), Choquelimpie (25), La Coipa (42), Pascua (30) and Cachi Laguna (75), may be attributed to upward increases in silver contents in HS systems, as indeed is documented at La Coipa (Oviedo *et al*, 1991). Alternatively, magma chemistry may be invoked as the basic control of Ag/Au ratio, as is assuredly the case at the gold-deficient Potosí silver deposit (Sillitoe *et al*, 1998).

Extremely shallowly eroded HS deposits retain parts of the steam-heated environment, generated above paleo-water tables, and zones of silicification marking the paleo-water table positions (Sillitoe, 1993; Figures 2 and 3). Most of the partially preserved steam-heated zones are located in the western Americas where aridity resulted in substantially lower mid- to late Cenozoic erosion rates than those that characterised much of the Southeast Asian and western Pacific regions. The acid-leached rock that characterises the steam-heated environment is generated by absorption of H_2S-containing steam in groundwater, and oxidation of the H_2S in vadose zones above paleo-water tables. Acid-leached rock comprises powdery, fine-grained cristobalite (a low-temperature silica polymorph) and/or alunite and, where pH is not so low, kaolinite is stabilised. Progressive or intermittent lowering of paleo-water tables during hydrothermal activity, say in response to uplift and valley incision, causes overprinting of HS mineralisation and its altered wallrocks by the steam-heated environment. Mineralised vuggy quartz, silicification and massive sulphide seem to be stable during this process, but the argillic haloes to mineralisation are readily transformed to cristobalite and/or alunite. As a consequence, shallow HS deposits are not only overlain by acid-leached rock, but also partly flanked by it (Figure 7), as observed at Paradise Peak (Sillitoe and Lorson, 1994), Yanacocha (Turner, 1998), Pierina (Volkert, McEwan and Garay, 1998), Pascua, La Coipa (Coipa Norte), Tambo and Cachi Laguna. Paleo-water table silicification seems to be developed best in permeable lithologies, in part due to the effects of lateral fluid outflow, and generally occurs as massive chalcedonic quartz after original opal, as observed spectacularly at Furtei (R H Sillitoe, unpublished data). Hydrothermal brecciation of these silicified horizons is commonplace. Hot-spring sinter does not accumulate at paleosurfaces above HS systems because of the inhibiting effect of acidity on silica precipitation (Sillitoe, 1993).

Acid-leached rock of steam-heated origin and paleo-water table silicification are generally barren of precious and base metals, which are not susceptible to volatile transport under the low-temperature conditions prevailing in and immediately beneath the steam-heated environment. Mercury, however, is mobile under such conditions and may be concentrated in acid-leached rock as cinnabar (eg Paradise Peak: Sillitoe and Lorson, 1994; Yanacocha: Turner, 1998). The markedly elevated mercury contents of shallow HS ore at Paradise Peak and La Coipa may be attributed to the effects of the steam-heated overprint (Sillitoe and Lorson, 1994). Although localised gold leaching and reconcentration under late-stage steam-heated conditions has been proposed at Kasuga (Hedenquist *et al*, 1994), how much gold, silver and copper are mobilised during widespread overprinting of the steam-heated environment remains undocumented, although clearly enough of the precious metals remained to make ore at Paradise Peak and La Coipa.

Approximately half of the HS deposits considered herein are observed to accompany volcanic domes or dome complexes, a common volcanic setting for epithermal deposits in general (Sillitoe and Bonham, 1984). Moreover, as many as ten of the deposits are hosted by central-vent volcanoes with or without associated domes (Table 1). Therefore, the paleosurfaces above

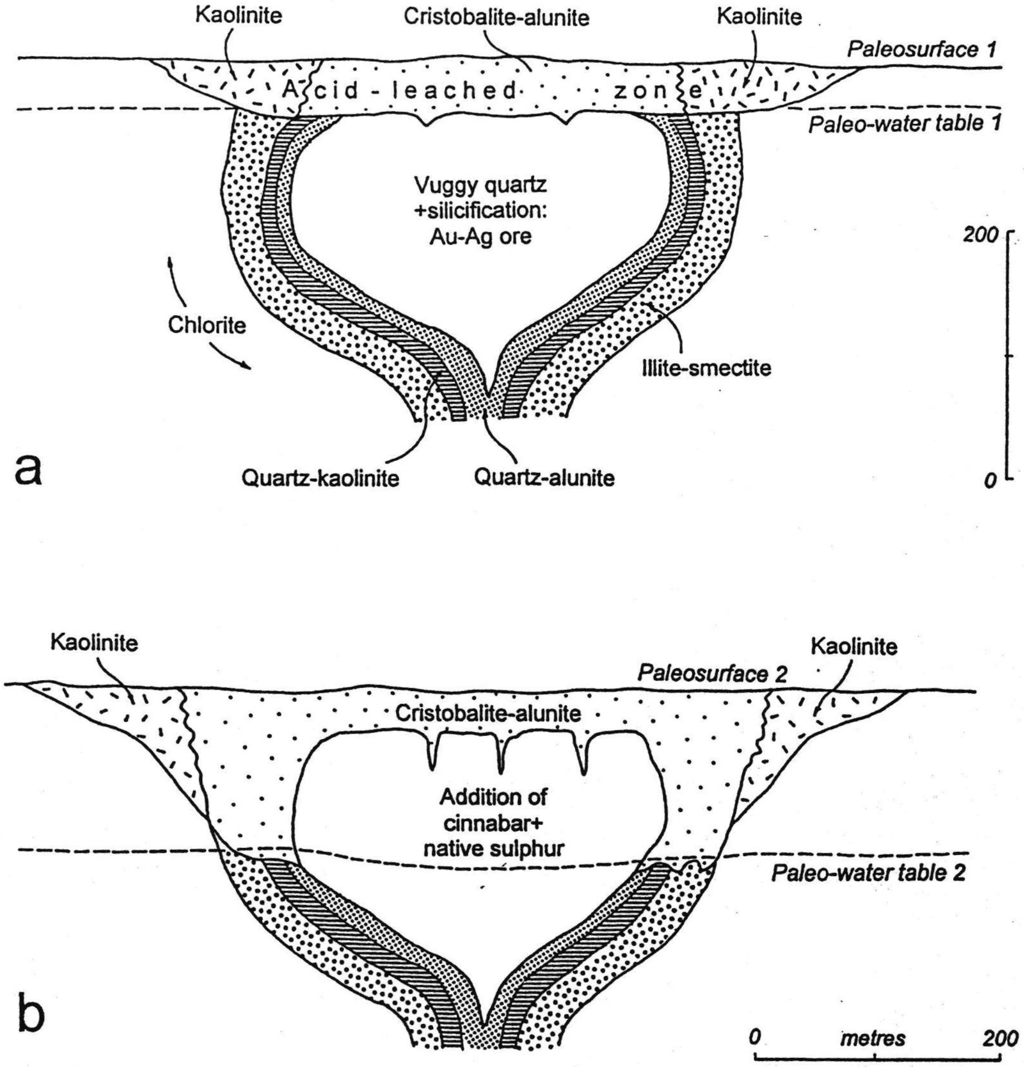

FIG 7 - Schematised development of the steam-heated environment in shallow HS systems: a. acid-leached zone located in the vadose zone above paleo-water table 1, which is the upper limit of gold/silver ore hosted by vuggy quartz/silicification and enveloped by quartz-alunite, quartz-kaolinite, illite-smectite and chlorite alteration; and b. acid-leached zone overprinted on the gold/silver orebody in response to descent of the paleo-water table to position 2 causing conversion of the marginal illite-smectite and chlorite alteration zones to acid-leached rock and addition of cinnabar plus native sulphur to both it and the vuggy quartz/silicification. The degree of precious-metal mobilisation caused during steam-heated overprints is uncertain.

many HS systems are likely to have been topographic highs. There are several exceptions to this generalisation, however, of which Pueblo Viejo, formed immediately beneath a tranquil lake environment (Kesler *et al*, 1981), is perhaps the most obvious. In the El Indio belt of northern Chile, however, flat-lying outliers of lacustrine sedimentary rocks dated at 5.4 - 7.6 Ma (Martin, Clavero and Mpodozis, 1997) are the youngest stratigraphic unit in the vicinities of several deposits (Pascua, Tambo) which, in view of the near synchroneity of the HS deposits (7.4 - 8.0 Ma; Table 1), suggests that mineralisation was active beneath lakes. Although some active HS systems may be capped by acidic crater lakes (Hedenquist, 1995), the geological evidence for an absence of active volcanic edifices in the El Indio belt at the time of HS mineralisation suggests that the lakes more likely occupied structurally defined depressions, perhaps akin to some of the modern central Andean salars. Some of these lacustrine sedimentary rocks in the El Indio belt underwent acid leaching in the steam-heated environment, thereby supporting the evidence provided by the deposits themselves for syn-hydrothermal descent of the paleo-water tables.

In view of the evidence for the formation of some HS deposits in lake environments, it is not surprising that volcanogenic massive sulphide (VMS) deposits of HS affinity are recognised in shallow submarine settings (Sillitoe, Hannington and Thompson, 1996). Indeed, it is easy to envisage the fairly rapid conversion of submarine to subaerial conditions, and *vice versa*, in island arcs. The contiguous Lerokis and Kali Kuning deposits in Wetar island, Indonesia, are included in Table 1 as the type example. The steep-sided bodies of massive, partly brecciated pyrite and their enveloping zones of friable barite that were exploited as gold-silver ore (Sewell and Wheatley, 1994) are believed to have been generated by replacement of felsic volcanic rocks immediately beneath the seafloor. Copper-bearing sulphides, including covellite, enargite and tennantite, were introduced late in the hydrothermal evolution of the systems (R H Sillitoe, unpublished data), as they were in most subaerial HS deposits. Recent submarine investigations of the Desmos caldera in the eastern Manus back-arc basin off Papua New Guinea have revealed emission of highly acidic (pH=2.1), sulphate-rich fluid of direct magmatic parentage (Gamo *et al*, 1997) and seafloor

basaltic andesite altered to a pyrophyllite- and alunite-bearing advanced argillic assemblage containing iron sulphides, enargite and covellite (Gena *et al*, 1998).

ZONING IN HS SYSTEMS

The descriptions of HS systems presented herein reveal the existence of marked vertical zoning with respect to mineralisation style, alteration, mineralogy and metal content (Figure 8), some of the features reported previously by Sillitoe (1995) and Corbett and Leach (1998).

As discussed above, mineralisation is predominantly disseminated and veinlet in style in the deepest, porphyry-hosted parts of HS systems, where downward penetration of alteration and mineralisation is controlled by a variety of structural and lithological features that enhance permeability. At shallower levels, in the deep epithermal environment, structurally controlled siliceous and massive sulphide bodies, commonly associated with hydrothermal breccia, become dominant. At still shallower epithermal levels, lithological control is pre-eminent and the largest deposits tend to be hosted by vuggy residual quartz and accompanying silicification, with or without the development of hydrothermal breccia.

The alteration accompanying HS systems displays a generalised upward change from quartz-sericite through quartz-dickite and/or quartz-pyrophyllite at deeper levels to vuggy residual quartz and quartz-alunite at shallower levels, a sequence reflecting the decrease of temperature and consequent increase in acidity of the ascendant acidic fluids (eg Giggenbach, 1997). However, dickite and pyrophyllite persist into the shallower parts of some systems, especially in the alteration haloes to ledges. Silicification also becomes prominent in the shallowest parts of systems, probably as a result of cooling and decrease in acidity resulting from fluid-rock interaction and admixture of the ascendant fluid with huge volumes of meteoric water. Nevertheless, somewhat more restricted bodies of silicification and vuggy quartz do occur in the deep parts of systems, where they may have been controlled by former deep aquifers and permeability barriers, respectively. High-temperature advanced argillic assemblages, containing andalusite, corundum and/or topaz occur in the deeper parts of some lithocaps (Sillitoe, 1995), but do not appear to be widespread in the deep HS deposits and prospects considered herein, although they have been reported locally (eg Agua Rica: Perelló *et al*, 1998; Bor: Jankovic, 1990). Peripheral alteration haloes also change upwards as a result mainly of temperature decline, with the absence of epidote from the shallow epithermal parts of systems being an especially prominent feature. Barite is commonplace in HS systems, but becomes particularly abundant at shallow levels in some of them (Summitville, Tambo, Potosí, Bor, Chelopech), as well as characterising the HS VMS environment (Sillitoe, Hannington and Thompson, 1996). The shallow HS bodies may retain some of the barren acid-leached rock generated above and alongside them in the steam-heated environment above paleo-water tables.

The deep porphyry-hosted parts of HS systems are dominated by high sulphidation-state copper±iron sulphides, particularly bornite, digenite, chalcocite and covellite, although subsidiary amounts of enargite and related sulphosalts are also widespread. Upwards, enargite and related sulphosalts become more abundant and generally predominate over the copper±iron sulphides throughout the epithermal environment. Luzonite, as the low-temperature dimorph of enargite, would be predicted to become more abundant at the expense of enargite upwards (Corbett and Leach, 1998), although this is apparently not a widely observed change. Enargite-rich mineralisation, especially in the deep epithermal environment, may show a downward transition to tennantite-chalcopyrite in its root zone (Figure 2), although this assemblage is not a significant component of the still deeper porphyry environment. Both deep porphyry-hosted and deep epithermal parts of HS systems tend to be dominated by copper, with gold possessing by-product status, whereas Au/Cu ratios seem to increase notably in the shallow epithermal environment, although the masking effects of oxidation obscure much of the evidence in many western American deposits. Shallow epithermal mineralisation commonly possesses covellite as the principal copper±iron sulphide mineral, some of it as a

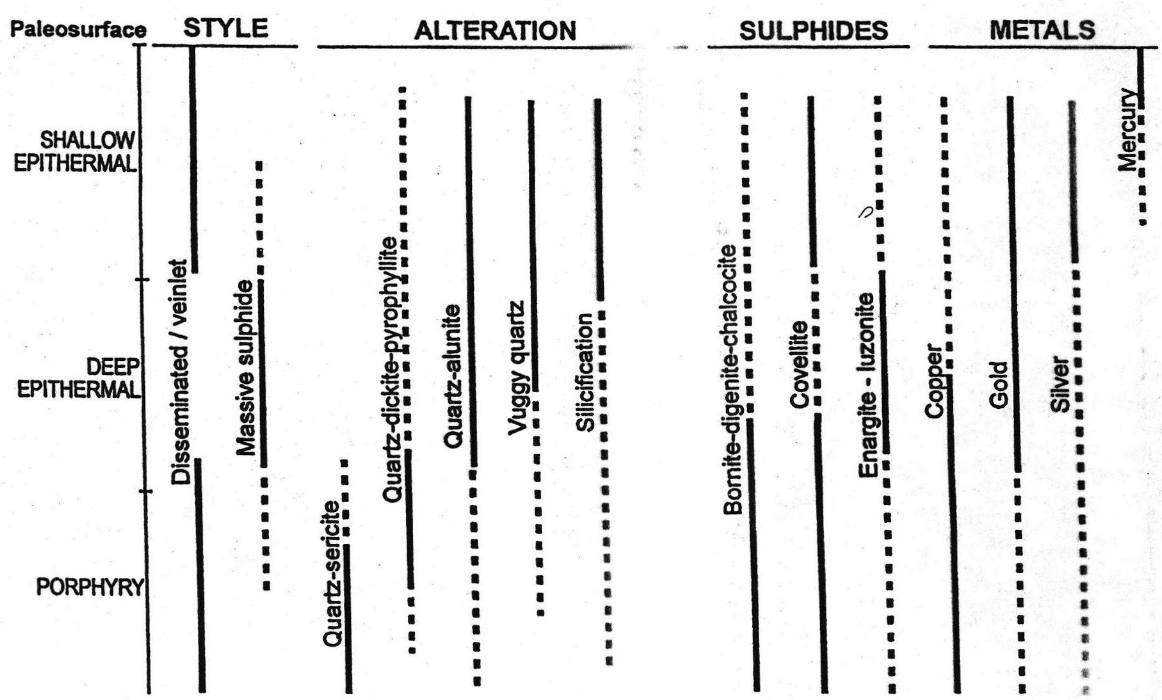

FIG 8 - Main aspects of vertical zoning of mineralisation style, al pes, sulphide species and metals in HS sys

late-stage addition with native sulphur. As noted above, there are elevated Ag/Au ratios in some shallow HS systems, although silver-poor deposits like Tambo (Ag/Au=~1) and Kasuga (~0.3) are notable exceptions. Antimony and tellurium are also described as metals occurring more abundantly in the shallow parts of systems (Corbett and Leach, 1998), as indeed the former is at Paradise Peak (Sillitoe and Lorson, 1994). However, no consistent zonal position for antimony and tellurium is discernible, and paragenetically late tellurides are abundant even in some deep HS deposits (eg Bisbee: Criddle, Stanley and Eady, 1989). The surficial parts of systems that were subjected to steam-heated conditions are characterised by elevated mercury contents and a general lack of anomalous amounts of other metals (eg Paradise Peak, La Coipa).

Some of the copper in the porphyry-hosted parts of HS systems may have been remobilised from earlier K-silicate assemblages and reprecipitated under HS conditions with sericitic and/or advanced argillic alteration (eg Brimhall and Ghiorso, 1983), rather than being introduced directly from underlying magma chambers by brines or volatiles. This process seems to have resulted in increased copper concentrations but, at least in some deposits (eg Wafi: R H Sillitoe, unpublished data), partial removal of gold. Notwithstanding the fact that some copper and gold may be differentially remobilised from pre-existing porphyry copper-gold mineralisation, introduction of most of these metals to the epithermal HS environment is suspected to be largely direct via magmatic fluid (see above).

Lateral, as well as vertical, zoning is a prominent feature of some HS systems. Within the HS parts of most systems, there is little available data regarding lateral changes; however, an increase of Ag/Au ratio, from 2/1 in the middle to 20/1 at the margins, is documented for the Summitville deposit (Gray and Coolbaugh, 1994) and tennantite instead of enargite characterises the fringes of the MM deposit (Sillitoe *et al*, 1996). Zinc and lead occupy a marginal position with respect to many HS systems but, as in the case of many porphyry copper deposits, these metals are commonly present at geochemically anomalous levels only and fail to become concentrated sufficiently to constitute deposits or even occurrences. However, about one-third of the HS deposits and prospects considered herein, including shallow, intermediate-level and deep examples, are marked by the presence of peripheral zinc, lead, silver and/or gold deposits or occurrences (Table 1).

These base- and precious-metal concentrations, mostly of vein type, are located beyond advanced argillic alteration and are of low-sulphidation (LS) epithermal type (eg White and Hedenquist, 1995). The marginal veins (Figure 3) range from crustiform banded, sulphide- and base metal-poor quartz±carbonate examples at Choquelimpie, El Indio and Motomboto to sulphide- and base metal-rich quartz±carbonate examples at Chinkuashih and Lepanto (the Victoria deposit: Cuison *et al*, 1998), which are the two principal vein varieties distinguishable throughout the LS epithermal environment (Sillitoe, 1993). All these distal precious-metal veins, with the exception of Victoria at Lepanto, are economically subordinate to the related HS mineralisation. Economic superiority is also a characteristic of the replacement zinc-lead-silver deposits developed in carbonate rocks distally with respect to the Colquijirca HS system (Vidal, Proaño and Noble, 1997), although those at Bisbee were less valuable than the more proximal copper-gold-bearing pipes and mantos. The disseminated pyrite-gold mineralisation in meta-sedimentary rocks alongside the porphyry-hosted Wafi HS copper-gold deposit (Erceg *et al*, 1991) is also believed to possess LS affinities, although it is partly hosted by several, apparently earlier advanced argillic assemblages.

These LS veins and carbonate-replacement bodies are physically separate from the HS parts of the systems (Figure 3) and commonly possess different structural and lithological controls. This observation and the absence of any obviously transitional mineralisation support the notion that two discrete fluids were involved: an oxidised and acidic one in the central parts of systems and a reduced and near-neutral pH one on their margins. The precise origin of the marginal LS fluid remains enigmatic, although its ability to concentrate zinc, lead, silver and/or gold invites comparison with the fluid responsible for deposition of the same metal suite at greater depths on the fringes of porphyry copper deposits (eg Jerome, 1966). If this comparison is valid, it is difficult to avoid the suggestion that wallrock interaction accompanied by temperature decline influenced the HS to LS change, albeit without any evidence for mineralisation by transitional fluids.

None of the peripheral base- and precious-metal mineralisation included in Table 1 has been dated radiometrically but, where ages are available, the HS is slightly older than the nearby LS mineralisation (eg by some 0.3 my in the Baguio district, Philippines: Aoki *et al*, 1993). This relative timing seems to be reversed in the case of the Monywa district, however, where Win and Kirwin (1998) reported overprinting of intermediate argillic alteration around peripheral LS veins by an advanced argillic assemblage.

SUPERGENE MODIFICATION OF HS SYSTEMS

HS systems undergo supergene oxidation and enrichment where climatic and geomorphological conditions are appropriate. As a result, most HS deposits and prospects in the arid and semi-arid parts of the western Americas possess appreciable supergene profiles, whereas most of those in the tropics of Southeast Asia and the western Pacific region, with the exceptions of Kasuga (Hedenquist *et al*, 1994) and Nalesbitan (Sillitoe *et al*, 1990), are characterised by only limited supergene modification (Table 1).

Sulphide oxidation in HS systems is markedly controlled by rock permeability and penetrates deeply in places, up to 400 m at Yanacocha and elsewhere, as indeed it also does in some LS epithermal deposits (eg Round Mountain, Nevada: Sander, 1988). The permeability that permits oxidation is commonly provided in HS deposits by vuggy residual quartz and hydrothermal breccia of several kinds, whereas sulphidic rocks remain at relatively shallow depths where argillic alteration predominates. Indeed, in some deposits, the oxide/sulphide interface occurs at the base and margin of the ore zone and is controlled by the contacts between siliceous and argillic rocks. Nevertheless, oxide/sulphide interfaces are commonly subhorizontal at the district scale, like the water tables that controlled them (eg Paradise Peak: Sillitoe and Lorson, 1994). The pyrite contents and pyrite/copper-bearing sulphide ratios of HS systems are typically high so there is more than enough supergene acid generated to cause near total leaching of copper from oxidised zones, which are characterised by jarosite- and hematite-rich limonites and, where enargite or luzonite is abundant, by scorodite and other arsenic-bearing minerals. Locally, however, the neutralisation capacities of mineralised siliceous rock are so low that hydrolisation of ferric sulphate in supergene solutions to precipitate limonite takes place only in external alteration haloes; hence, the oxidised ore itself may be deficient in limonite. Oxidation of semi-massive to massive sulphides in HS systems results in incompetent materials ranging from friable quartz to powdery, multicoloured limonite. The volume loss in some oxidised massive sulphide bodies is commonly sufficient to induce widespread disruption caused by compaction and even collapse brecciation (eg Paradise Peak: Sillitoe and Lorson, 1994).

Advanced argillic assemblages are stable under acidic supergene conditions, but enveloping argillic alteration zones containing illite, smectite and chlorite are highly susceptible to kaolinisation. Hence, hypogene and supergene kaolinite zones may be juxtaposed in the supergene profiles developed over some HS deposits (Figure 9). Their distinction is not easy, although there is generally more hydrothermal quartz in hypogene kaolinite zones.

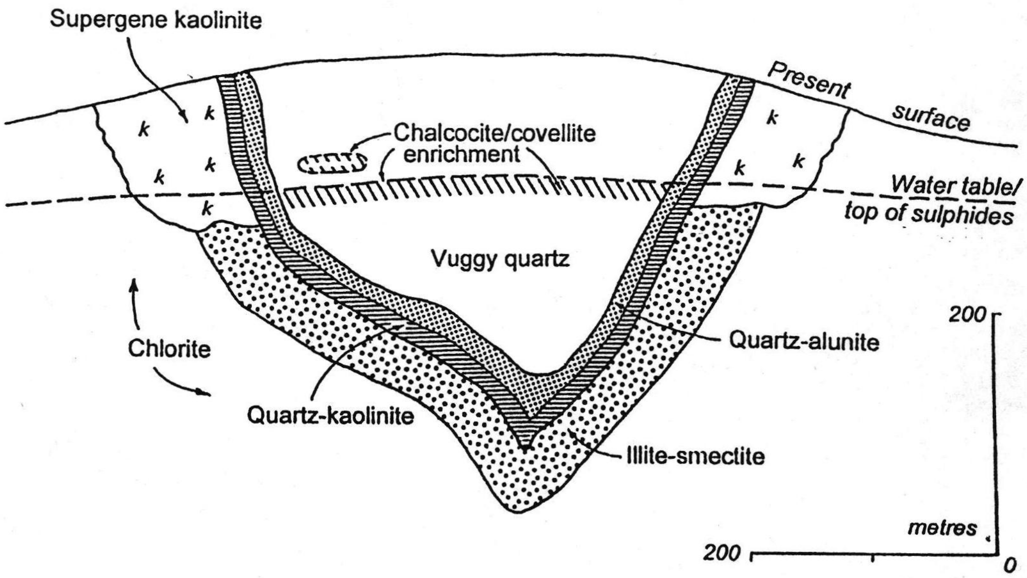

FIG 9 - Schematised weathering profile developed in the upper parts of HS deposits. Sulphide oxidation above the water table is commonly incomplete because of permeability variations that result in remnant sulphidic patches in leached capping or gossan. The uppermost parts of the sulphide zone and any remnant sulphide patches undergo supergene chalcocite/covellite enrichment, the required copper being provided by the sulphide oxidation. The acidic solutions generated during sulphide oxidation cause kaolinisation of the outer illite-smectite and chlorite alteration zones, while the advanced argillic alteration assemblages remain stable. The result is a lateral transition from hypogene to supergene kaolinite zones in the weathered parts of systems.

Chemical solution and concentration of gold and silver do not seem to be widespread during the oxidation of HS systems, although local gold enrichment in faults and fractures (eg Summitville: Stoffregen, 1987) and at the water table (eg Golden Hill) is reported. Nevertheless, overall precious-metal contents may be enhanced because of the reduction in rock density resulting from the oxidation of semi-massive and massive sulphides.

Most oxidised HS deposits reveal the presence of at least minor amounts of supergene chalcocite and/or covellite in the uppermost parts of their underlying sulphide zones. Supergene chalcocite and covellite are generally powdery (sooty) as opposed to the massive and, locally, crystalline character of their hypogene counterparts. Where HS systems are copper-rich and subjected to major supergene oxidation and enrichment events, as in the case of Chuquicamata and El Guanaco in northern Chile during the late Eocene to mid-Miocene interval (Sillitoe and McKee, 1996), oxidised and enriched zones are high-grade and economically pre-eminent. The low neutralisation capacities of the sericitic and advanced argillic alteration and the high permeabilities provided by the steep veins in these two deposits optimised the oxidation and enrichment processes (Sillitoe, 1995).

Several workers have proposed that all or part of the sulphide oxidation observed in HS systems is hypogene in origin (eg John *et al*, 1991; Siddeley and Araneda, 1990). The cited evidence, besides the great depths of oxidation, generally involves the intimate intermixture of oxidised and sulphidic rocks, especially the presence of partly oxidised breccia clasts in unoxidised chalcedonic matrices. Such observations, however, may be explained readily on the basis of permeability contrasts during weathering, with the matrix quartz being less permeable than the siliceous clasts in the case of the breccia example (eg Paradise Peak: Sillitoe and Lorson, 1994). Hypogene oxidation and accompanying covellite enrichment and gold introduction have been proposed recently for the largely oxidised Pierina deposit based on the existence of centimetre- to metre-sized patches of unoxidised rock above the main base of oxidation and the presence of covellite rims to these patches (Noble *et al*, 1997; Volkert, McEwan and Garay, 1998). However, such marginally enriched sulphide patches are commonplace in HS systems (Figure 9), as indeed they are in porphyry copper deposits lacking HS additions, and are a normal facet of permeability-controlled differential oxidation in the weathering environment. The covellite or, in other deposits, chalcocite rims are generated because the edges of the sulphidic patches act as redox fronts exactly like the underlying main oxide-sulphide interfaces.

Hypogene oxidation is considered to be an unlikely mechanism for sulphide destruction in HS systems. If the process really operated, it would be difficult to explain why the supposed evidence for such hypogene oxidation is observed at a variety of paleo-depths, from the shallow epithermal to the deep porphyry levels, in HS systems, but only in the semi-arid and arid arc terranes along the eastern side of the Pacific Ocean. Any putative hypogene fluid capable of sulphide oxidation would have to be chloride- and bromide-rich, rather than dilute as observed in fluid inclusions (Arribas, 1995), in order to account for the silver haloids (eg cerargyrite, embolite) that are widespread accompaniments to gold in the deeply developed oxidised zones at several deposits, including Paradise Peak (Sillitoe and Lorson, 1994), La Coipa (Oviedo *et al*, 1991) and Potosí. Furthermore, iron sulphides are observed to be stable through to the present surface in actively forming steam-heated zones at the tops of modern HS (and LS) systems, although the iron sulphides appear to be most abundant near their bases in proximity to paleo-water table positions.

EXPLORATION PRIORITIES IN HS SYSTEMS

HS systems offer a variety of exploration objectives, which depend on the level of exposure that is observed as well as the local geological conditions. The exploration priorities include: large-tonnage disseminated copper±gold mineralisation in the deep porphyry-hosted parts of systems; carbonate-replacement mantos and pipes in the deep subvolcanic parts of systems;

high-grade gold-bearing veins and hydrothermal breccias formed as late-stage products in the epithermal parts of systems; and large-tonnage, low-grade, lithologically controlled mineralisation in the shallow epithermal parts of systems that have been subjected to deep and thorough supergene oxidation.

Deep porphyry-hosted HS overprints tend to be large in volume (several tens to several hundreds of million tonnes) and copper-rich, being dominated by copper sulphides, principally digenite, chalcocite and covellite. Moreover, even immature supergene enrichment can appreciably increase copper sulphide contents in the upper parts of these HS sulphide zones. These deposits are generally more valuable where they are unoxidised or oxidised only shallowly, hence especially in Europe, Southeast Asia and the western Pacific region. This is because they are commonly best treated by conventional flotation, in the same manner as gold-rich porphyry copper deposits in general. Where hypogene plus supergene copper sulphides predominate, solvent extraction-electrowinning (SX-EW) may be a viable processing alternative, as commenced recently at Monywa (Win and Kirwin, 1998). Enargite and luzonite contents ideally should be low because these minerals are not easily recoverable in standard SX-EW plants and result in unattractive arsenic-rich flotation concentrates. However, in the case of regions like northern Chile, where mature supergene profiles are developed, oxide copper zones amenable to SX-EW treatment as well as enrichment zones suitable for flotation or SX-EW may both be present, as at Chuquicamata. Mature supergene enrichment is an effective means of eliminating substantial amounts of the arsenic from enargite- and luzonite-rich ores. Deep oxidation is a particularly negative feature of porphyry-hosted HS copper mineralisation if gold contents are appreciable, unless supergene copper leaching has been extremely thorough. Should oxide copper minerals remain in the oxidised parts of such deposits, gold recovery by cyanidation is difficult if not impossible.

Copper- and gold-rich mantos and pipes associated with quartz-pyrite replacement may be anticipated in the deep parts of HS systems emplaced into carbonate rocks. In arc terranes characterised by widespread shelf carbonates, such as Peru, Honduras-Nicaragua, western USA and New Guinea, the potential for this HS deposit type seems to have been largely overlooked. The discovery of the large San Gregorio zinc-lead-silver deposit in the Colquijirca district (Vidal, Proaño and Noble, 1997) also draws attention to the potential offered by the LS fringes of such carbonate-hosted HS systems.

The only large bonanza epithermal gold deposits of HS type are Goldfield and El Indio, where late-stage hydrothermal breccias and quartz veins, respectively, carried the exploited multi-ounce ore. Although the number of examples is few, the existence of high gold contents in relatively small late-stage overprinted veins at Summitville and Lepanto and in breccias at Chinkuashih and Rodalquilar suggests that generation of late-stage gold concentrations from fluid of somewhat lower sulphidation states may be fairly commonplace in the intermediate to shallow levels of HS systems. Therefore, even isolated bonanza-grade gold intersections obtained during exploration drilling require careful investigation in case they are the evidence for volumetrically restricted, but gold-rich, late-stage additions to the systems. Furthermore, the recent discovery of the >5-million ounce Victoria LS epithermal vein system alongside the Lepanto HS copper-gold deposit (Cuison *et al*, 1998) emphasises the potential for major gold concentrations peripheral to the generally more prominent HS parts of systems. Indeed, areas immediately beyond advanced argillic lithocaps are rarely explored in any detail, but clearly deserve attention.

The largest HS gold deposits, like Pueblo Viejo, Yanacocha, Pierina and Pascua, are located in the shallow epithermal parts of HS systems, where suitable lithological permeability is available. Preferred host rocks seem to be ignimbrite, other types of tuffs, volcaniclastic units and lacustrine sediments, especially the first of these. Welded, not only poorly or non-welded, ignimbrite seems to be a favoured host rock for HS mineralisation. Although some of these large deposits possess relatively high-grade ore (eg Pueblo Viejo, Pierina), there is a tendency for them to be characterised by relatively low average gold contents. Consequently, supergene oxidation is a requirement for economic viability and, hence, they are an exploration objective principally in the western Americas for climatic rather than hydrothermal reasons. The siliceous, porous and locally friable nature of these oxidised gold ores makes them ideal for heap-leach cyanidation, in some cases without preparatory crushing. The extremely shallow settings of some of these large gold deposits means that all or parts of them may be concealed beneath barren acid-leached rock formed in the steam-heated environment and, therefore, lack any appreciable geochemical signature. Major tonnages of ore are concealed in this manner at several deposits (eg Pascua, Coipa Norte at La Coipa).

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